

Models of solar irradiance variability and the instrumental temperature record

Steven L. Marcus

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

Michael Ghil and Kayo Ide

Department of Atmospheric Sciences and Institute for Geophysics and Planetary Physics,
University of California, Los Angeles, CA 90095-1567

Abstract. The effects of decade-to-century (Dec-Cen) variations in total solar irradiance (TSI) on global mean surface temperature T_S during the pre-Pinatubo instrumental era (1854-1991) are studied by using two different proxies for TSI and a simplified version of the IPCC climate model. TSI anomalies based on solar-cycle length (CL) and solar-cycle decay rate (CD) proxies can account for most of the warming observed up to 1976, but anthropogenic forcing is needed to explain the subsequent sharp increase in T_S . The time series of CL-solar and anthropogenic radiative forcing resemble each other, making it difficult to separate their effects in the instrumental T_S record. Results using the CD-based irradiance values, however, allow tighter constraints to be placed on both TSI variability and terrestrial climate sensitivity, and underscore the inability of solar forcing alone to explain the recent global warming.

Introduction

Variability of the total solar irradiance (TSI) is a potentially important contributor to changes in global mean temperatures on time scales longer than a few years. Striking correlations between the instrumental T_S record, extending back nearly a century and a half, and observable solar features, such as the amplitude and length of the sunspot cycle, have suggested that solar variations may indeed have a strong impact on decade-to-century (Dec-Cen) changes in global mean temperature T_S [Reid, 1997, and references therein]. In the absence of a convincing physical link between these observed solar features and TSI, however, the role of solar variability in the terrestrial climate record is difficult to quantify. We examine here the implications of some simple physical

assumptions regarding the origin of Dec-Cen variability in TSI for the way it might affect the instrumental record of T_S .

Models of Solar Variability

TSI variations on the order of 0.1% have been detected within a solar cycle by satellite-borne radiometers [e.g., *Willson and Hudson*, 1991] and successfully modeled in terms of observable photospheric features [e.g., *Pap et al.*, 1994; *Lean et al.*, 1998]. While their effects may be detectable in records of land surface and ocean temperatures [e.g., *Stevens and North*, 1996; *White et al.*, 1997; *Lawrence and Ruzmaikin*, 1998], these sub-decadal fluctuations are too small to account for a significant fraction of the 0.6 °C increase in T_S recorded over the last century [*IPCC*, 1996]. Cycle-to-cycle variability in TSI is most plausibly linked to longer-period variations in the intensity of convective heat transport from the solar interior to the photosphere [e.g., *Baliunas and Jastrow*, 1993; *Hoyt and Schatten* 1993, 1997], which may be detectable through their concomitant effects on observable solar features. In particular, Hoyt and Schatten argue that more intense convection leads to a more rapid decay of individual sunspots and a shorter solar cycle, and thus can account for the apparent (inverse) correlation between cycle length and irradiance in the sun as well as in sunlike stars [e.g. *Baliunas and Soon*, 1995].

We investigate here the implications of this assumption for solar effects on the instrumental temperature record. To do so, we use simplified models for cycle-to-cycle TSI variations and the response of the terrestrial mean temperature T_S to net radiative forcing. Their simplicity allows us to thoroughly test the sensitivity of results to changes in model assumptions and parameter values, and avoids the complications posed by the regionally heterogeneous nature of anthropogenic forcing and the “fingerprint” of the climate system’s response [cf. *Schneider*, 1994].

Variations $F(t)$ in the convective transport of heat to the photosphere from its mean are modeled as proportional to the decay rate of the solar cycle, defined as the reciprocal of the time interval between the epochs of a solar cycle maximum t_M and the subsequent minimum t_m :

$$F_1(t_m) = k_1 / (t_m - t_M) ; \quad (1)$$

k_1 is an unknown proportionality constant. The convective anomaly F_1 for a cycle is defined as occurring at the time t_m of solar minimum, when the photospheric features associated with TSI variations within a cycle are largely absent [e.g., *Lean et al.*, 1998].

For comparison with previous studies, we also consider a formulation in which the convective heat flux anomaly is modeled as inversely proportional to the cycle length, defined as the interval between successive minima:

$$F_2(t_{m+1/2}) = k_2 / (t_{m+1} - t_m) ; \quad (2)$$

here k_2 is an unknown proportionality constant, and the convective anomaly F_2 is defined at the time $t_{m+1/2}$ which is midway between the epochs of successive minima t_m and t_{m+1} . Note that since t_m and t_M can vary independently, the flux anomaly F_1 modeled in terms of the cycle decay rate has twice the temporal degrees of freedom contained in the F_2 anomaly series, for which adjacent cycle lengths both depend on the epoch t_m of the intervening minimum.

Applying an arbitrary smoothing to the solar record can considerably alter its climatic impact [Kelly and Wigley, 1992]. We choose instead to model the effect of convective heat-flux variability on TSI in terms of a first-order autoregressive (AR-1) process:

$$dW/dt + W/\tau = k F(t) ; \quad (3)$$

here W is the solar irradiance anomaly, $F(t)$ is the anomalous convective heat transport derived from either the cycle decay-rate (CD) model (Eq. 1) or the cycle length (CL) model (Eq. 2), k is an unknown proportionality constant, and τ is a relaxation time for the convective anomaly. The relaxation time $\tau \sim L^2/\nu$ was estimated by choosing the kinematic eddy viscosity ν of the convective zone near the lower limit of a plausible range [$\nu \sim 10^{12} - 10^{13} \text{ cm}^2\text{sec}^{-1}$, cf. *Zeldovich et al.* 1983] and the relevant length scale L as the depth of the convective zone (about 1/3 of the solar radius); this yields $\tau = 12.6 \text{ yr}$.

TSI anomalies were calculated from *Lassen and Friis-Christensen's* [1995] epochs for t_m and t_M (their Tables 1 and 2), using both the CD and CL formulations for the convective heat flux anomaly. Due to the linearity of the AR-1 process, the proportionality constants k_1 and k_2 in Eqs. (1) and (2) can be combined with the constant k in Eq. (3) into a single unknown scaling factor for

each of the irradiance curves, which are plotted in Fig. 1 in arbitrary units. The cycle-length (CL) model irradiance has a clear upward trend over the 140-year span shown in the figure, while the cycle decay (CD) rate model shows a sharp TSI increase between 1880 and 1937, with a subsequent decrease to values below the 140-year average. The implications of these characteristics of the modeled TSI for Sun-climate relations are explored next.

Global Mean Temperature Response

We computed the response of the global mean temperature T_S to changes in radiative forcing by applying a simplified version of the IPCC upwelling-diffusion model [Kattenberg *et al.*, 1996]; no distinction is made in this model version between land and ocean or northern and southern hemispheres. A fraction $\Pi = 0.2$ of the temperature change is assumed to be downwelled by the thermohaline circulation, which is characterized by a fixed, globally averaged upwelling velocity of 4 m yr^{-1} . Ensembles of runs were performed starting from an assumed zero temperature anomaly in 1850, in which the climate sensitivity S (defined as the equilibrium increase in T_S for doubled CO_2) and solar forcing amplitude I_0 (defined as the difference between the minimum and maximum values given by the irradiance curves in Fig. 1) were varied over fixed ranges. The model results for T_S were evaluated in terms of the percentage of variance accounted for in the Jones *et al.* [1994] reconstruction of T_S that spans the pre-Pinatubo instrumental temperature record (1854-1991). Possible effects of the "cold start" [e.g., Hasselmann *et al.*, 1993] were addressed by examination of runs initialized in 1765 with IPCC-estimated anthropogenic forcing; the impact of this initialization on the model's temperature variation during the instrumental period was minimal.

We first performed a series of experiments using only the anomalous solar forcing given by the cycle-length (CL) TSI, with amplitudes ranging up to $I_0 = 1.80 \text{ Wm}^{-2}$; at the same time, the model's climate sensitivity was varied from 0.5 to $5.0 \text{ }^\circ\text{C}$ (Fig. 2a, upper panel). The highest amount of variance in the Jones *et al.* [1994] T_S record that can be accounted for by the CL proxy model is 55%; it was obtained for a net irradiance amplitude of $I_0 = 0.90 \text{ Wm}^{-2}$, which (assuming a planetary albedo of 30%) corresponds to a variation in the solar "constant" of 0.38% during the

last century. *Lean et al.* [1992] used linear regression of solar Ca II (HK) emission with respect to satellite-measured irradiance to estimate the TSI deficit for a noncycling state (such as the Maunder Minimum, ca. 1700) as 0.24%, which scales to a peak-to-peak variation of ~0.14% during the last century; *Zhang et al.*'s [1994] corresponding estimates, based on brightness changes in a sample of sunlike stars, span a range from about this value to an irradiance change over the last century of ~0.5%. Although consistent with a limited stellar sample, therefore, the amplitude of the CL-solar forcing required to fit the observed T_S record is considerably in excess of Dec-Cen variability inferred from the solar HK-irradiance relationship.

The best-fit climate sensitivity for the CL solar-only case ($S = 5.0$ °C) also exceeds plausible estimates for this parameter (1.5 - 4.5 °C, cf. *IPCC*, 1996; note that values of S within the IPCC range would imply greater TSI amplitude). The simulated T_S variation using the optimal (I_0 , S) pair roughly matches the Jones et al. record until 1976 (Fig. 2a, lower panel), but even with these relatively large solar forcing and sensitivity parameters, the climate model is unable to capture the subsequent rapid increase which occurred prior to the Pinatubo eruption in 1991. This latter part of the record is expected *a priori* to be subject to the strongest anthropogenic effects; the failure of the simulated temperature to match the recent warming lends further support to the idea that this warming is not due to solar forcing alone.

To assess the relative contribution of human activities to the observed warming, we performed another series of model runs including the estimated radiative effects of greenhouse gases and sulfate emissions [*IPCC*, 1996], with the latter scaled to produce a global-mean forcing of -0.6 Wm⁻² in 1990. Note that the temporal profile of the net anthropogenic forcing (dotted line in Fig. 1) is similar to the solar irradiance profile generated by the CL model (with a correlation coefficient $r = 0.57$); both show an overall upward trend during the last century. The anthropogenic signature in the global mean temperature record, therefore, will resemble that of the CL-derived irradiance, making it difficult to distinguish their effects on the observed Dec-Cen variations of T_S .

The addition of anthropogenic forcing to the CL-derived solar irradiance increases the maximum T_S variance accounted for to 72% (Fig. 2b, upper panel), with the recent warming, in

particular, now fully captured (Fig. 2b, lower panel). The best-fit climate sensitivity has been reduced to 2.1 °C, well within the IPCC range. The implied solar forcing of 0.65 W/m² (or TSI variation of 0.27% during the last century) is also well within *Zhang et al.'s* [1994] estimated range for stellar variability, although it is still about twice the amplitude inferred from *Lean et al.'s* [1992] solar irradiance-HK relation. The "trade-off" between the effects of the CL-solar and anthropogenic forcing manifests itself as an extended, hyperbolic-shaped region in the I_0 - S plane, for which the explained T_S variance is nearly the same as that obtained with the optimal parameters. The red-shaded area in Fig. 2b (upper panel), in particular, shows that the observed T_S record is consistent with relatively large CL-solar variations ($I_0 > 1.2$ W/m², or ~0.5% TSI) during the last century, provided the climate sensitivity is restricted to values below the IPCC range ($S < 1.5$ °C). While these results indicate that the T_S record cannot be explained by CL-derived irradiance alone, therefore, they do not rule out a large role for solar forcing in producing the warming observed over the last century.

To examine the dependence of solar-forcing effects on the proxy model used to infer Dec-Cen TSI variability, we repeated the above calculations using the cycle decay-rate (CD) irradiance profile (solid line in Fig. 1). For the solar-forcing-only experiments the distribution of associated T_S variance in the I_0 - S plane (Fig. 3a, upper panel) is quite similar to that obtained with the CL model, although its magnitude is diminished by about one-half. As for the CL model, the optimal temperature history simulated with CD-solar forcing reproduces the observed T_S variation fairly well until about 1976 (Fig. 3a, lower panel). Whereas the CL-derived irradiance shows a substantial increase since about 1970, however, the CD profile decreases monotonically from 1937 to 1980, with only a modest subsequent recovery (Fig. 1). The climate model responds to the CD-solar forcing with a steady temperature decrease since mid-century, causing large deviations from the observed T_S record during the recent warming.

The addition of anthropogenic forcing to the CD irradiance more than doubles the associated T_S variance (Fig. 3b, upper panel), reaching the same maximum (72%) obtained with the combined anthropogenic and CL forcing. The bulk of the improvement evidently comes from the last part of

the record, where the cooling produced by the CD solar-only forcing (Fig. 3a, lower panel) has been replaced by an accelerated warming (Fig. 3b, lower panel) which fits the observed upward trend of T_S within observational error [cf. *Jones et al.*, 1997]. The best-fit solar forcing has been reduced from 0.67 Wm^{-2} for the combined CL case to 0.52 Wm^{-2} , reflecting the poorer match between declining CD irradiance and the recent warming. The corresponding Dec-Cen TSI variability (0.22%) is roughly consistent with *Lean et al.'s* [1992] estimate of the maximum possible Maunder irradiance deficit.

Discussion and Conclusions

The relative roles of solar and anthropogenic forcing in producing climate change over the instrumental era, as deduced from the CL and CD experiments, are summarized in Table 1. For both irradiance proxies, the model results indicate that the steep rise in temperature observed in the early part of the century (1910-1940; see *Ghil and Vautard* [1991]) was largely caused by Dec-Cen solar variability. The warming documented in the full (1854-1991) instrumental T_S record is dominated by anthropogenic effects, however, with the CL-derived irradiance accounting for only 21% of the over-all temperature increase, while the CD-solar forcing actually offsets the warming over this time interval by a small amount (3%). Since the same anthropogenic forcing (dotted line in Fig. 1) was prescribed for all experiments, the climate sensitivity S required to fit the observed temperature record is greater, by almost 50%, for the CD irradiance profile.

The choice of a proxy irradiance model, therefore, can strongly influence the inferred role of solar forcing in recent climate change, as well as the quasi-equilibrium sensitivity of the terrestrial climate system deduced from the instrumental temperature record [see also *Wigley et al.*, 1997]. Due to the near "orthogonality" ($r = 0.07$) of the CD-solar and anthropogenic forcing profiles (cf. Fig. 1), in particular, the subset of (I_0, S) values which is compatible with the observed T_S record forms a more compact region in parameter space than was obtained for the CL irradiance (compare upper panels of Figs. 2b and 3b). The combination of very high values of solar forcing ($I_0 > 1.2$

Wm⁻²) and very low values of climate sensitivity ($S < 1.5$ °C) found to be compatible with the CL profile is thus effectively excluded by the CD irradiance model.

To the extent that the CD model more directly incorporates the physical processes responsible for Dec-Cen irradiance variability, therefore, these findings underscore the inability of solar forcing alone to explain recent temperature increases [see also *Solanki and Fligge*, 1998]. Since both irradiance models (combined with anthropogenic forcing) account for nearly the same amount of year-to-year T_S variance (72%), however, the results presented here cannot be used to ascertain which proxy TSI series best captures Dec-Cen solar variability. An accurate reconstruction of solar effects on global climate requires the development of robust and reliable proxy models which are related as directly as possible to the underlying mechanisms. The identification of turbulent convective processes which affect heat transport into the photosphere, as well as solar-cycle and spot decay rates, seems a promising approach [*Hoyt and Schatten*, 1993, 1997]. Further refinements in both its theoretical and observational aspects will be needed, however, to accurately constrain the solar contribution to recent climate change.

Acknowledgments. This work was supported by NOAA grant NA96AANAG0350. We thank J. Feynman, J. Pap and A. Ruzmaikin for interesting discussions and references.

References

- Baliunas, S., and R. Jastrow, Evidence on the climate impact of solar variations, *Energy* 18, 1285-1295, 1993.
- Baliunas, S., and W. Soon, Are variations in the length of the activity cycle related to changes in brightness in solar-type stars? *Astrophys. J.* 450, 896-901, 1995.
- Ghil, M., and R. Vautard, Interdecadal oscillations and the warming trend in global temperature time-series, *Nature* 350, 324-327, 1991.
- Hasselmann, K., R. Sausen, E. Maier-Reimer, and R. Voss, On the cold start problem in transient simulations with coupled atmosphere-ocean models, *Clim. Dyn.* 9, 53-61, 1993.
- Hoyt, D. V., and K. H. Schatten, A discussion of plausible solar irradiance variations, 1700-1992. *J. Geophys. Res.* 98, 18895-18906, 1993.
- Hoyt, D. V., and K. H. Schatten, *The Role of the Sun in Climate Change*, Oxford University Press, 279 pp., 1997.

- IPCC, *Climate Change 1995: The Science of Climate Change*, J.T. Houghton et al. (eds.), Cambridge University Press, 572 pp, 1996.
- Jones, P. D., T. M. Wigley, and K. R. Briffa, in *Trends '93: A Compendium of Data on Global Change*, T.A. Boden et al. (eds.), pp. 603-608, 1994.
- Jones, P. D., T. J. Osborn, and K. R. Briffa, Estimating sampling errors in large-scale temperature averages, *J. Clim.* 10, 2548-2568, 1997.
- Kattenberg, A., et al., Climate models - projections of future climate. In *Climate Change 1995: The Science of Climate Change*, J.T. Houghton et al. (eds), pp 285-357, 1996.
- Kelly, P. M., and T. M. L. Wigley, Solar cycle length, greenhouse forcing and global climate, *Nature* 360, 328-330, 1992.
- Lassen, K. and E. Friis-Christensen, Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate, *J. Atmos. Terr. Phys.* 57, 835-845, 1995.
- Lawrence, J. K., and A. A. Ruzmaikin, Transient solar influence on terrestrial temperature fluctuations, *Geophys. Res. Lett.* 25, 159-162, 1998.
- Lean, J., A. Skumanich, and O. White, Estimating the Sun's radiative output during the Maunder Minimum, *Geophys. Res. Lett.* 19, 1591-1594, 1992.
- Lean, J., J. Cook, W. Marquette, and A. Johannesson, Magnetic sources of the solar irradiance cycle, *Astrophys. J.* 492, 390-401, 1998.
- Pap, J. M., C. Frohlich, H. S. Hudson, and S. K. Solanki, eds., *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge Univ. Press, 1994.
- Reid, G. C., Solar forcing of global climate change since the mid-17th century, *Clim. Change* 37, 391-405, 1997.
- Schneider, S. H., Detecting climate change signals: Are there any "fingerprints"?, *Science* 263, 341-346, 1994.
- Solanki, S. K., and M. Fligge, Solar irradiance since 1874 revisited, *Geophys. Res. Lett.* 25, 341-344, 1998.
- Stevens, M. J., and G. R. North, Detection of the climate response to the solar-cycle, *J. Atmos. Sci.* 53, 2594-2608, 1996.
- White, W. B., J. Lean, D. R. Cayan, and M. D. Dettinger, Response of global upper ocean temperature to changing solar irradiance. *J. Geophys. Res.* 102, 3255-3266, 1997.
- Wigley, T. M. L., P. D. Jones, and S. C. B. Raper, The observed global warming record: what does it tell us? *Proc. Natl. Acad. Sci. USA*, 94, 8314-8320, 1997.
- Willson, R. C., and H. S. Hudson, The Sun's luminosity over a complete solar cycle, *Nature* 351, 42-44, 1991.
- Zeldovich, Y. B., A. Ruzmaikin and D. D. Sokoloff, *Magnetic Fields in Astrophysics*, Ch. 11, Gordon & Breach Publishers, NewYork/London, 1983.
- Zhang, Q., W. H. Soon, S. L. Baliunas, G. W. Lockwood, B. A. Skiff, and R. R. Radick, A method of determining possible brightness variations of the Sun in past centuries from observations of solar-type stars, *Astrophys. J.* 427, L111-L114, 1994.

Solar Model	Century-Scale Irradiance Change	Implied Climate Sensitivity	Solar Contribution to Warming	
			1854–1991	1910–1940
CL	0.27%	2.1°C	21%	70%
CD	0.22%	3.0°C	-3%	58%

Table 1. Results from experiments using combined anthropogenic and solar forcing.

Figure Captions

Fig. 1. Time series of radiative-forcing terms used to drive the climate model. TSI anomalies derived from solar cycle decay (CD) rate and solar cycle length (CL) proxies are shown in arbitrary units (left ordinate), and the anthropogenic forcing is shown in Wm^{-2} (right ordinate).

Fig. 2. (a) Results of climate simulations using the anomalous TSI profile given by the solar cycle length (CL) proxy. The upper panel shows the percentage of variance in the Jones et al. (1994) yearly series of global mean surface temperature associated with the simulated T_s series, using the climate sensitivity (I_0) and solar scaling (S) parameters defined by the abscissa and ordinate, respectively. The lower panel shows the corresponding temperature history obtained using the (I_0 , S) pair that yields the highest variance; note that since the climate model simulates only temperature changes, both the simulated and observed series (solid red and blue curves, respectively) have been adjusted to have zero mean over the time interval plotted. The dashed red lines show 2σ confidence intervals derived by Jones et al. [1997] for decadal temperature errors, and are plotted to indicate a plausible range of observational deviations from a "perfect" model. (b) as in (a), with the anthropogenic radiative forcing added to the CL-solar forcing.

Fig. 3. (a) As in Fig. 2a, using the anomalous TSI profile given by the solar cycle decay (CD) rate proxy. (b) As in Fig. 3a, with the anthropogenic radiative forcing added to CD-solar forcing.

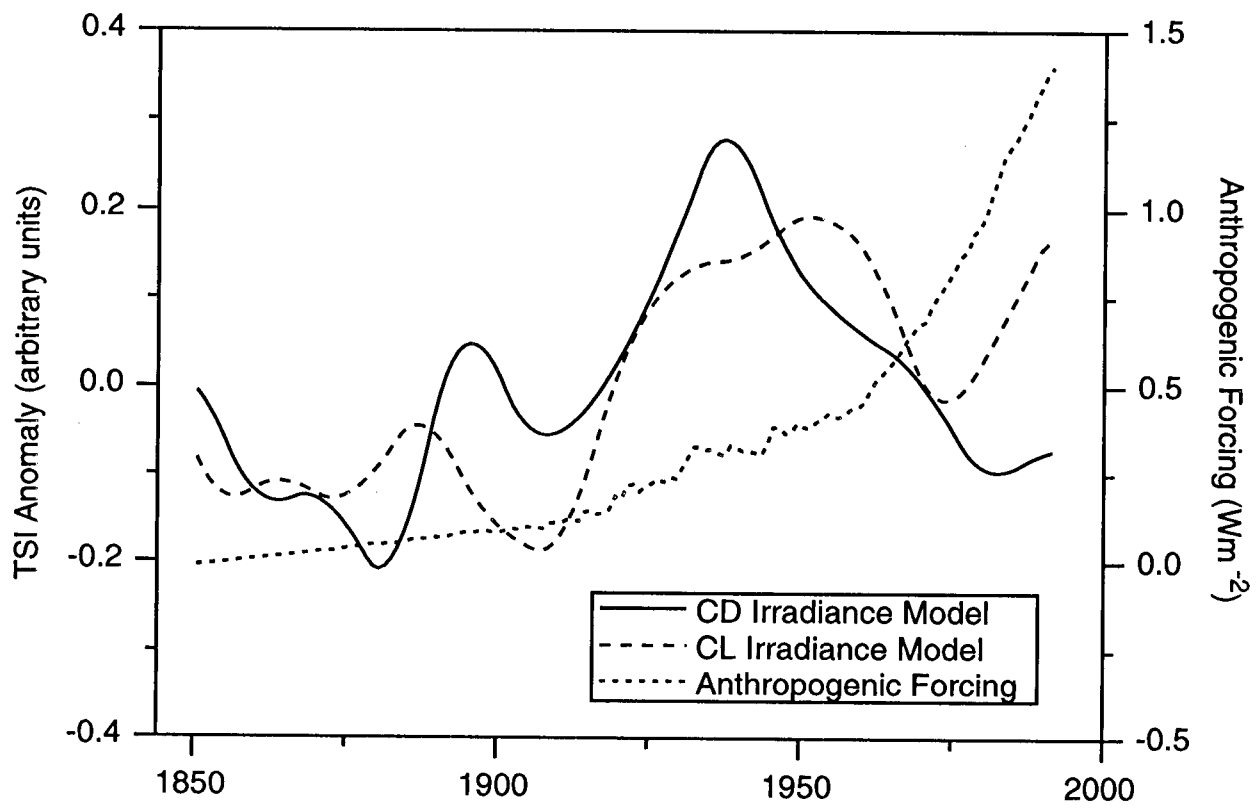


Fig. 1

Solar Cycle Length Model

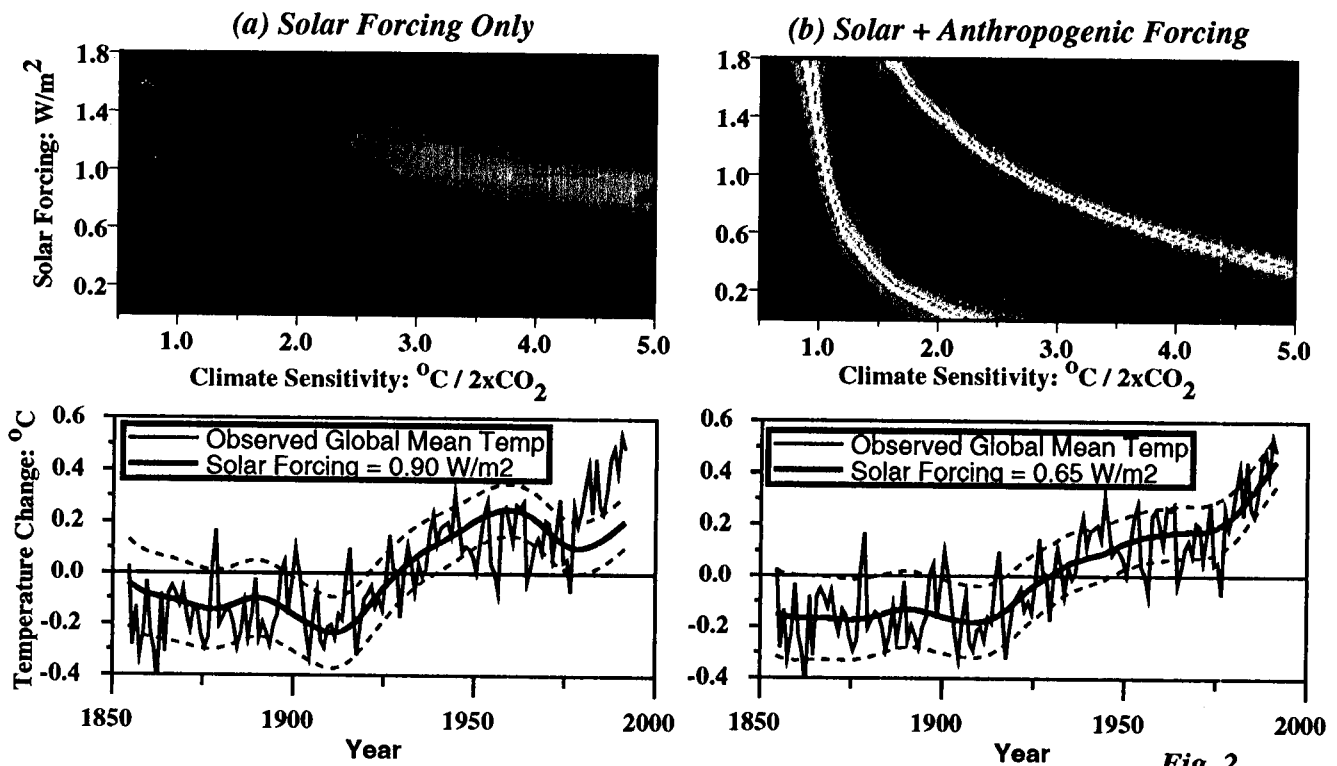
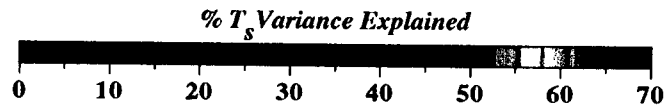


Fig. 2



Solar Cycle Decay Model

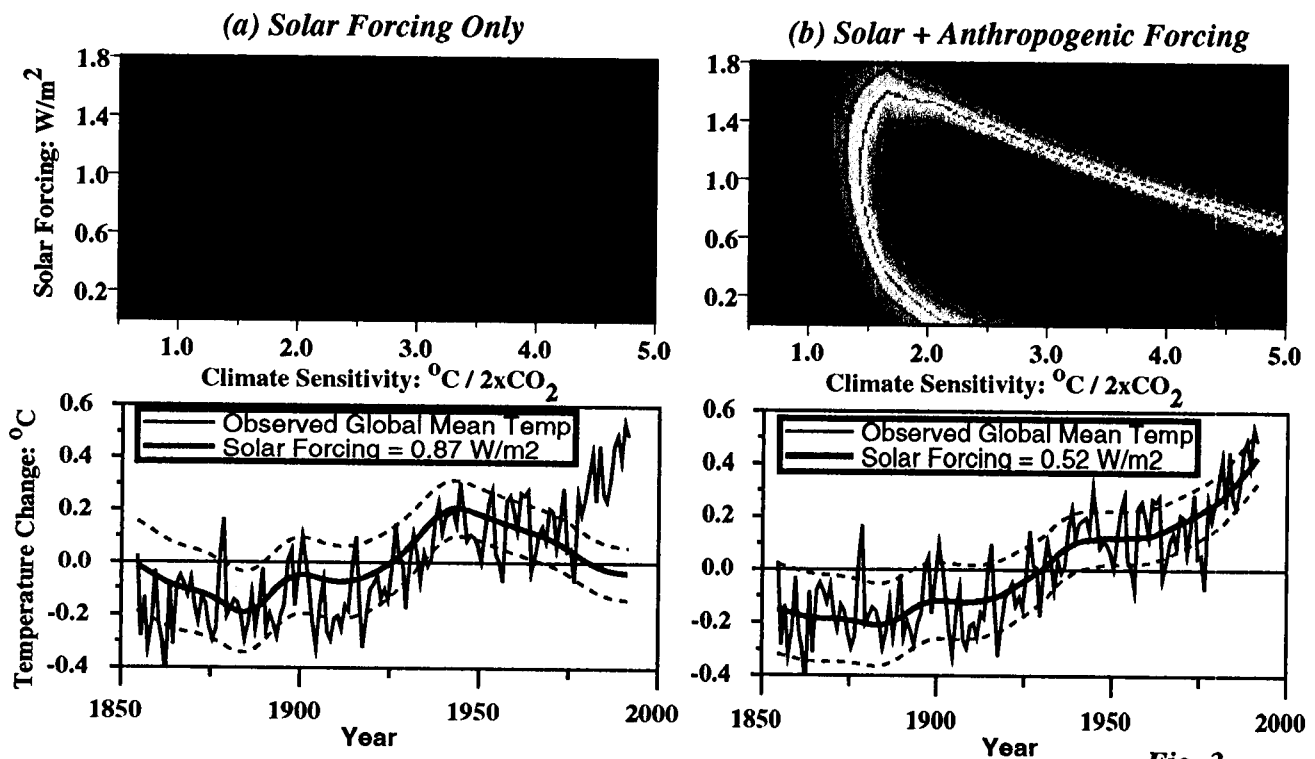


Fig. 3